Parsec-scale VLBI observations of TeV gamma-ray sources

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Abstract

Very Long Baseline Interferometry (VLBI) observations provide the only means of imaging the parsec-scale structure of active galactic nuclei. VLBI observations of extragalactic TeV gamma-ray sources and candidates are reported, and the inferences that can be drawn on the jet behaviour between the TeV variability-scale and the VLBI milli-arcsecond–scale are discussed. It is apparent that TeV gamma-ray sources have slower apparent jet speeds than EGRET-detected GeV gamma-ray sources.

1. Introduction

Very Long Baseline Interferometry (VLBI) is a powerful technique enabling milli-arcsecond angular resolution imaging to be undertaken at radio frequencies. In VLBI observations, widely spaced radio telescopes simultaneously observe the same celestial radio source, digitize the radio signal, and record the data on magnetic tape. The tapes are later brought together at a correlator for the data to be combined.

Early VLBI observations revealed the presence of apparent superluminal motion in the core of some active galactic nuclei (AGN), with a jet component being ejected from the core at a speed apparently greater than the speed of light. It is now accepted that the apparently superluminal motion is produced by highly relativistic plasma moving at a small–to–moderate angle to the line of sight. The apparent speed (in terms of the speed of light), β_{app}, is given by

$$\beta_{app} = \frac{\beta \sin\theta}{1 - \beta\cos\theta}$$

which as θ approaches 0° and β approaches 1, can result in values of β_{app} in excess of 1. For a given value of β, the largest apparent superluminal speed is observed

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when $cos\theta = \beta$. Naturally, when $\theta = 0$, no motion is observed. The detection of superluminal motion was a key piece of evidence for the relativistic outflow of material in the jets of AGN (and, more recently, galactic "micro-quasars"). Relativistic jets can also be characterised by their Doppler factor,

$$\delta = \frac{1}{\gamma(1 - \beta cos\theta)},$$

which for fixed β peaks at $\theta = 0$.

A detailed multi-epoch monitoring of EGRET blazars has been undertaken at 22 GHz and 43 GHz with the Very Long Baseline Array (VLBA) by [6]. This program revealed that the apparently superluminal speeds detected for these of EGRET-detected blazars were much faster than for the general population of bright compact radio sources. It was also found that times of high gamma-ray flux coincided with ejections of superluminal components from the cores of a significant fraction of EGRET blazars [7].

It is naturally of interest to see if this trend is followed by TeV sources. TeV gamma-ray emitting AGN have on occasions displayed dramatic variability of their TeV emission. A TeV flare in Mrk 421 had a timescale as short as 15 minutes, requiring $\delta \geq 9$ from compactness arguments [4], and the rapid variability observed in 1ES 1959+650 in May and June 2002 places a similar limit on the Doppler factor [5]. Fits of specific emission models to the spectra and variability of these sources can require even higher Doppler factors, e.g., $\delta \sim 40$ for Mrk 421 [11] and $\delta \sim 15$ for Mrk 501 [8]. One might, therefore, expect that VLBI observations of TeV gamma-ray sources would reveal super-luminal motions of the parsec-scale jet components.

2. Observations

We have undertaken VLBI multi-epoch observations of the reported TeV sources Mrk 421, Mrk 501, 1ES 1959+650, PKS 2155−304 and 1ES 2344+514. For Mkn 421 and Mkn 501, we have compiled VLBI observations at frequencies between 2 and 15 GHz from several sources: the U.S. Naval Observatory Radio Reference Frame Image Database [3], the VLBA 2 cm survey [9], and dedicated VLBA and VLBI Space Observatory Programme (VSOP) observations. For the remaining sources, we have undertaken three-epoch monitoring at 15 GHz with the VLBA. Preliminary results have been presented elsewhere [1,13].

Despite the high inferred Doppler factors from TeV observations, the multi-epoch VLBI observations of Mrk 421 [12] and Mrk 501 [2] have revealed that the apparent speeds measured in the jets of these blazars are sub-luminal. This is in

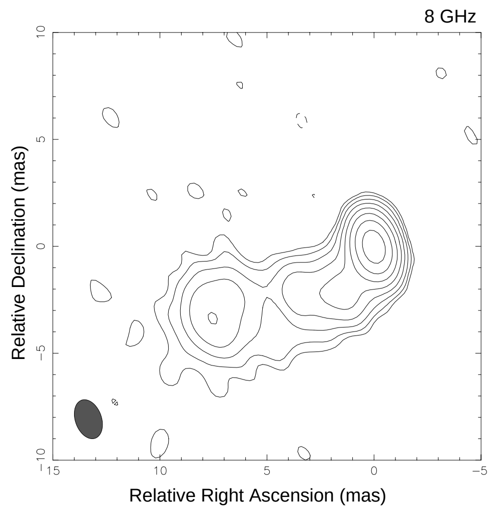

Fig. 1. Image of Mkn 501 at 8 GHz from an RRFID observation in April 1996. An angular separation of 1 mas corresponds to a projected linear distance of 0.72 pc for $H_0 = 65$ km s^{-1} Mpc^{-1}. The map peak is 540 mJy/beam. The beam, 1.9 mas × 1.2 mas at a position angle of 20°, is shown at bottom left.

contrast to previous claims of superluminal motion in both sources, which were generally based on fewer epochs of lower resolution data.

Our multi-epoch VLBA observations of 1ES 1959+650, and of TeV candidates 1ES 2344+514 and PKS 2155−304 reveal that within errors, the jet components in these sources are also consistent with sub-luminal speeds [14].

A summary of apparent speeds of parsec-scale jet components is given in Table 1. This is adapted from [14] with a revised value for the speed of component C2 for Mkn 501 [2].

3. Why are the jets sub-luminal?

It is clear that the apparent jet speeds in the few TeV sources detected to date differ significantly from the predominantly super-luminal speeds measured for EGRET blazars. A blazar may of course be detected with both TeV and GeV telescopes. Here we use 'TeV blazar' to refer to those sources whose inverse Compton spectra peak at TeV energies (also called 'blue blazars') and 'GeV' or 'EGRET blazar' for those sources whose inverse Compton spectra peak at GeV energies (also called 'red blazars').

Doppler factors of 10 or more are inferred from TeV variability, but fast apparent speeds are not observed in the VLBI observations. Three possibilities

Table 1. Apparent VLBI component speeds (adapted from [14]). Components are numbered from the outermost component inwards. Apparent speeds are determined assuming $H_0 = 65$ km s^{-1} Mpc^{-1}.

Source	Monitoring period	Component	β_{app}
Mrk 421	Apr.1994 – Dec.1997	C4	0.2 ± 0.3
		C5	0.3 ± 0.1
		C6	-0.1 ± 0.1
Mrk 501	Apr.1995 – Jul.1999	C1	0.1 ± 0.2
		C2	0.6 ± 0.1
		C3	0.3 ± 0.1
		C4	0.0 ± 0.1
1ES 1959+650	Mar.2000 – Jul.2000	C1	0.1 ± 1.1
		C2	-0.2 ± 0.8
PKS 2155−304	Mar.2000 – Jun.2000	C1	4.6 ± 3.8
1ES 2344+514	Oct.1999 – Mar.2000	C1	1.3 ± 0.8
		C2	0.5 ± 0.8
		C3	-0.2 ± 0.8

have been suggested:

(i) A small angle to the line-of-sight. If θ is very close to zero, then superluminal motion will not be observed. The doppler factor of the jet can remain at the inferred TeV value of $\sim$10, with the subluminal motion arising because the VLBI jet is aligned to within 1° of the line-of-sight.

(ii) A changing Doppler factor. It is possible that δ changes between the $\sim 10^{-4}$ pc TeV emitting region and the ~ 1 pc VLBI region. Bends in jets are observed on the parsec scale, but are not sufficient to reduce δ unless accompanied by a reduction in the bulk Lorentz factor also. In an electron-positron dominated jet, high energy electrons lose energy very efficiently to synchrotron radiation and inverse Compton scattering and so, if the slope of the electron energy spectrum is flat enough (< 2), most of the energy and momentum can be lost close to the base of the jet [10].

(iii) Unequal "pattern" and bulk flow speeds. The "pattern" speed refers to the speed inferred from the motion of the jet components observed in VLBI observations. It is quite possible, however, that this is in fact the motion of a shock along the jet, and the underlying plasma speed, or bulk flow speed, could have either a higher or lower value. Vermeulen & Cohen [15] show that ratios of pattern to bulk Lorentz factors ranging from ~ 0.5 to ~ 5 can fit the observed β_{app}

distribution of core-selected quasars. Extreme examples of this are the "stationary" components observed relatively commonly in AGN, even in those which have superluminal components (e.g., [6]). Jorstad et al. suggested that the stationary components within several parsecs of the core were associated with standing recollimation shocks caused by pressure imbalances at the boundary between the jet and the surrounding medium. In contrast, the stationary components further from the core tend to be associated with bends in the parsec-scale jet. However, it is not clear why the differing pattern and bulk speeds might apply to TeV sources but not GeV sources.

Since the jets of the three weaker sources are relatively smooth, it is also possible that a relativistically moving flow that smoothly declines in brightness may be sucessfully modelled (given the limited resolution of the data) as a series of stationary Gaussians, yielding a pattern speed of zero despite underlying relativistic flow. This possibility is being investigated.

4. TeV high states and new VLBI components?

As mentioned above, many of the flat-spectrum radio quasars detected by EGRET were found to have times of high gamma-ray flux that coincided with the extrapolated ejection epoch of a superluminal components from the cores [7]. In contrast, the dramatic, though short-lived TeV flaring of Mkn 421 in 1996 did not result in the emergence of a new component from the core. Similarly, the prolonged TeV high-state of Mrk 501 in 1997 has not resulted in the emergence of a new VLBI component. A new component would have been readily detectable if it had an apparent speed similar to C2 and C3 [2]. As discussed elsewhere [10, 12], this is suggestive that the energy in these flaring events is dissipated close to the core. Although the limited evidence to date suggests that TeV flares do not result in the emergence of new VLBI components, VLBI components are clearly ejected from these sources from time to time. It would be interesting to know (but, with the limited duty cycle of TeV observations, difficult to determine) whether such component ejections are accompanied by any TeV activity.

We are in the process of reducing a four-epoch VLBI campaign on Mrk 421, undertaken at 22 GHz with the VLBA, to determine whether the TeV high-state in early 2001 has resulted in the ejection of a new VLBI component.

5. Conclusions

The apparent speeds of the parsec-scale jet components in the few confirmed TeV gamma-ray emitting AGN are subluminal. Though the statistics are limited, the distribution of component speeds differs significantly from that of

EGRET sources. Possible explanations include a small angle to line-of-sight in TeV sources, a changing Doppler factor between the TeV scale and the VLBI scale regions, and unequal pattern and bulk speeds. Also, in contrast to the general behaviour of EGRET sources, there appears to be no emergence of new components associated with TeV high states.

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